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# Search for narrow $NN\pi$ resonances in exclusive $pp \rightarrow pp\pi^+\pi^-$ measurements

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## Abstract

Narrow structures in the range of a few MeV have been searched for in  $pp\pi^+$  and  $pp\pi^-$  invariant mass spectra ( $M_{pp\pi^+}$  and  $M_{pp\pi^-}$ ) obtained from exclusive measurements of the  $pp \rightarrow pp\pi^+\pi^-$  reaction at  $T_p = 725, 750$  and  $775$  MeV using the PROMICE/WASA detector at CELSIUS. The selected reaction is particularly well suited for the search for dibaryon resonances decoupled from  $NN$  and/or  $N\Delta$ . In the mass range  $2020 \text{ MeV}/c^2 < m_{\text{dibaryon}} < 2085 \text{ MeV}/c^2$  no narrow structures could be identified on the  $3\sigma$  level of statistical significance neither in  $M_{pp\pi^-}$  nor in  $M_{pp\pi^+}$  giving an upper limit (95% C.L.) for dibaryon production in this reaction of  $\sigma < 20 \text{ nb}$ .

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## 1. Introduction

With the realization of quarks being the basic building blocks of matter and of QCD being the appropriate theory of the strong interaction, the idea emerged that the substructure of baryons should lead to new types of states in the system of two baryons in addition to the “trivial” deuteron ground state and  $^1S_0$  virtual state. Indeed, QCD inspired models in the early eighties [1] predicted a large number of dibaryon states of basic  $6q$  structure. Despite a vast number of dedicated experiments in search of such states not a single one could yet be identified unambiguously; for a review see, e.g., [2]. However, the bulk of these searches was devoted to dibaryons which by their quantum numbers could couple to the  $NN$  and/or  $N\Delta$  channels. In these cases the dibaryon states can undergo a fall-apart decay and hence cannot be expected to have narrow widths. Their widths should rather be even larger than those of usual baryon resonances, which are in the order of 100 MeV and larger. Since such very broad dibaryon resonances would be difficult to sense in experiments, the failure of previous dibaryon searches could at least partly be explained in this way.

On the other hand dibaryon resonances, which by their quantum numbers are decoupled from the  $NN$  and  $N\Delta$  channels, may be expected to be rather narrow, notably if close to the  $NN\pi$  threshold. Actually, such states with  $I(J^P) = 0(0^-)$  and  $0(2^-)$  had been predicted by Mulders et al. [1] at a mass as low as  $m = 2.11 \text{ GeV}/c^2$ —though more recent theoretical work taking into account proper antisymmetrization [3] prefers the  $0^-$  state at a somewhat higher mass.

Another cause for a small decay width of a dibaryon resonance can be a dynamical suppression, e.g., due to large angular momenta involved in the decay. Such a candidate is the so-called inevitable dibaryon  $d^*$  with  $I(J^P) = 0(3^+)$ , a kind of fully stretched and deeply bound  $\Delta\Delta$  state. It is predicted [4] to have a mass in the range of 2070–2150  $\text{MeV}/c^2$  and a width of a few MeV only.

Recently a candidate for a  $NN$ -decoupled dibaryon state has been proposed for the explanation of an otherwise peculiar, resonance-like structure in the energy dependence of the forward angle cross section of the pionic double charge exchange (DCX) on nu-

clei  $A(\pi^+, \pi^-)B$  leading to discrete final states [5–8]. This structure, systematically observed on a wide range of nuclei with peak cross sections at incident energies of  $T_\pi \approx 40\text{--}70 \text{ MeV}$ , i.e., far below the  $\Delta$  excitation, has been successfully explained both in its energy and angular dependence by the assumption of the formation of a narrow  $NN\pi$  resonance, the so-called  $d'$ , with  $I(J^P) = \text{even}(0^-)$ ,  $m \approx 2.06 \text{ GeV}/c^2$  and  $\Gamma_{NN\pi} \approx 0.5 \text{ MeV}$  [5–8]. However, since this reaction takes place in the nuclear medium, subtle medium effects cannot be excluded as origin of this structure. In fact, there have been attempts to describe the observed resonance-like structures in special situations by conventional models [9–11], though a convincing description of the full observed systematics is still lacking.

In order to minimize the effects of the nuclear medium, the DCX reaction has also been carried out on  $^3\text{He}$  and  $^4\text{He}$  [12], i.e., on the lightest nuclei, where this reaction is possible. However, contrary to the situation with heavier nuclei, there is no longer a bound nuclear state in the exit channel, and the process leads to the nuclear continuum only. Unfortunately, this situation leads to a less pronounced signature of  $d'$  production, in particular, if collision damping of the  $d'$  resonance with the neighbouring nucleons is included [12]. Hence, the DCX measurements on the He isotopes finally have so far been inconclusive with regard to the existence of  $d'$ .

Also a search on the basic  $NN$  system has been carried out at MAMI with a high resolution and high statistics measurement [13] of the reaction  $d(\gamma, \pi^0)X$ . In the range  $2020 < m < 2100 \text{ MeV}/c^2$  no narrow structures had been found on the  $3\sigma$  level with upper limits in the range of a few microbarn for the production of isoscalar or isovector dibaryons. However, this limit is still an order of magnitude above the prediction for  $d'$  production [14] and hence not conclusive for this particular dibaryon candidate either.

## 2. Experiment

The only alternative reaction left in the basic  $NN$  system and simultaneously a potentially much more sensitive test of the  $d'$  hypothesis is the reaction  $NN \rightarrow NN\pi\pi$ , where  $d'$  can be produced associatively in a fixed target experiment for projectile beam

energies  $T_p > 710$  MeV, when assuming a mass of  $m_{d'} = 2.06$  GeV/ $c^2$ . The  $pp \rightarrow pp\pi^+\pi^-$  reaction is particularly well suited for this search, since both invariant mass spectra  $M_{pp\pi^+}$  and  $M_{pp\pi^-}$  can be observed simultaneously. If a resonance appears in both of these spectra, then its isospin has to be  $I = 2$ , if it shows up in  $M_{pp\pi^-}$  only, then  $I \leq 1$ . To this aim we have carried out exclusive measurements of the  $pp \rightarrow pp\pi^+\pi^-$  reaction at  $T_p = 725, 750$  and  $775$  MeV using the PROMICE/WASA setup [15] with a hydrogen cluster jet target at the CELSIUS ring. The ejectiles were detected in the angular range  $4^\circ \leq \Theta_{\text{lab}} \leq 21^\circ$ . Protons and pions were identified by the  $\Delta E - E$  method,  $\pi^+$  particles were in addition positively identified by the delayed pulse originating from  $\mu^+$  decay following the  $\pi^+$  decay at rest. This way the two-pion production events could be clearly separated from the huge background of charged  $\geq 3$ -prong events due to single  $\pi^0$  production with successive Dalitz decay or  $\gamma$  conversion into  $e^+e^-$ -pairs. As a test of the energy resolution we constructed the missing mass spectrum from identified  $pp\pi^+$  tracks and obtained a clean single peak at the  $\pi^-$ -mass with a width of  $\Gamma \approx 8$  MeV FWHM (see Fig. 1 in Ref. [16]). Eventually the four-momenta of the full  $pp\pi^+\pi^-$  events were reconstructed by kinematical fits with one over-constraint (1C) which requires that in the 3-particle missing mass  $MM_{pp\pi^+}$  is equal to the pion mass  $m_{\pi^-}$ . A total of 1163, 8016 and 9603  $pp\pi^+\pi^-$  events have been obtained at 725, 750 and 775 MeV, respectively.

### 3. Results

From Monte Carlo (MC) simulations of the detector response we expect an energy resolution of a few MeV in  $M_{pp\pi^+}$  similar to that obtained for the  $\pi^-$  peak in the 3-particle missing mass  $MM_{pp\pi^+}$ . Note that in the absence of a magnetic field  $\pi^-$  four-momenta have not been measured, only reconstructed. Hence the resolution in  $M_{pp\pi^+}$  cannot be improved by using the single-particle missing mass  $MM_{\pi^-}$ . For  $M_{pp\pi^-}$  the resolution is significantly better, since this spectrum being equivalent to the single-particle missing mass of the  $\pi^+$  is determined by the four-momentum of the detected  $\pi^+$  alone. For kinematical reasons the energy resolution is best at the high energy end of  $M_{pp\pi^-}$  and gets worse with decreasing  $M_{pp\pi^-}$

values. For the region of  $d'$ , i.e., near 2.06 GeV/ $c^2$ , we expect a resolution of FWHM = 3–4 MeV/ $c^2$ . Fig. 1 shows the  $M_{pp\pi^+}$  and  $M_{pp\pi^-}$  spectra obtained from the measurements at  $T_p = 750$  and 775 MeV. These spectra, which are not yet corrected for efficiency and acceptance, are compared to MC simulations including the detector response. The dotted lines show the result, assuming pure phase space for the reaction mechanism. The shaded areas show the result of a model calculation, which quantitatively reproduces all differential cross sections of the  $pp \rightarrow pp\pi^+\pi^-$  reaction at  $T_p = 750$  MeV [17]. In this model the reaction is assumed to proceed via the excitation of the  $N^*(1440)$  resonance with its subsequent decay into  $N\sigma$  and  $\Delta\pi$  channels. For a detailed discussion of the reaction process see Ref. [17], where also the differential cross sections for other invariant mass systems and angular distributions are presented. Within statistics the data are smooth, compare very favorably with the model calculations and, most importantly in the present context, show no narrow structures on the  $3\sigma$  level with the exception of the data bin at 2087 MeV/ $c^2$  in the  $M_{pp\pi^-}$  spectra just at the high-energy end of the experimental range covered in these experiments. This point will be discussed separately at the end of this section.

To increase the sensitivity to  $d'$  we next have imposed the condition  $M_{pp} < 1896$  MeV/ $c^2$  on events selected in  $M_{pp\pi^-}$ . This condition should enhance the events stemming from  $d'$  production relative to those from the conventional process, since  $d'$ —if of  $6q$  nature—should be smaller in volume than the interaction region of the conventional process. Hence the protons originating from the  $d'$  decay are expected to undergo a stronger final state interaction, which in turn would lead to an enhancement of events at low  $M_{pp}$  masses [18]. The expected difference in FSI enhancements between  $d'$  production and conventional process is borne out by comparing the  $M_{pp}$  spectrum calculated for the process via  $d'$  production (Fig. 4(c) in Ref. [18]) with the  $M_{pp}$  spectrum actually measured for the conventional process (Fig. 1 in Ref. [17]). The  $M_{pp\pi^-}$  spectra constrained by the  $M_{pp}$  condition are shown in the middle part of Fig. 1. Again we do not observe narrow structures of statistical significance with the exception of the data bin at 2087 MeV/ $c^2$ .

For  $T_p = 725$  MeV the expected location of a possible  $d'$  peak is already very close to the high-energy end

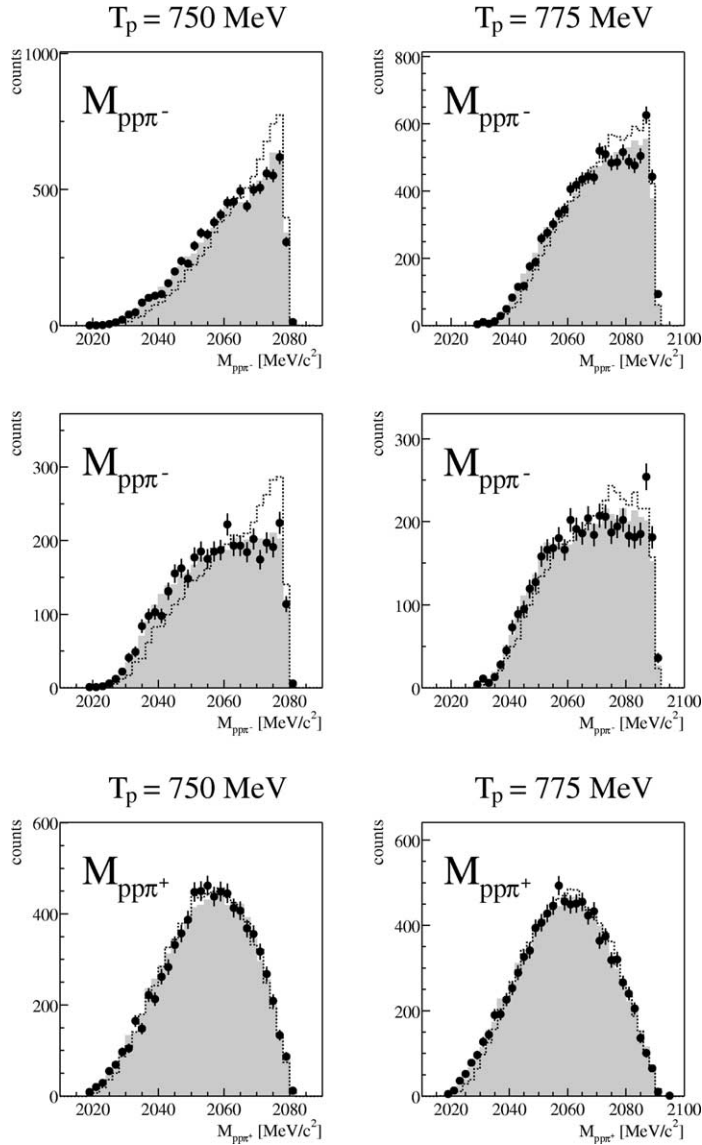


Fig. 1. Invariant mass spectra  $M_{pp\pi^+}$  and  $M_{pp\pi^-}$  obtained from the exclusive measurements of the  $pp \rightarrow pp\pi^+\pi^-$  reaction at  $T_p = 750$  MeV (left) and  $T_p = 775$  MeV (right). At the top the unconstrained  $M_{pp\pi^-}$  spectra are shown. The  $M_{pp\pi^-}$  spectra plotted in the middle part contain only events meeting the condition  $M_{pp} < 1896$  MeV/ $c^2$  (see text). At the bottom the unconstrained  $M_{pp\pi^+}$  spectra are shown. Note, that all these spectra are not yet corrected for detector acceptance and efficiency. The dotted lines represent a MC simulation (including the detector response) assuming pure phase space for the reaction process, the shaded areas represent a model calculation (see Ref. [17]), which quantitatively describes all differential cross sections of the reaction.

of the  $M_{pp\pi^-}$  spectrum, where kinematically the conventional 4-body phase space alone leads to a peak-like structure (see Fig. 2 in Ref. [19]). In this situation the resolution in  $M_{pp\pi^-}$  and the accumulated statistics turned out to be too low for a meaningful search for  $d'$ ,

while the situation is more favourable at  $T_p = 750$  and 775 MeV.

On the basis of roughly 1000 events obtained in a test run [16] at  $T_p = 750$  MeV preceding the high statistics runs presented here we had found a 4 MeV

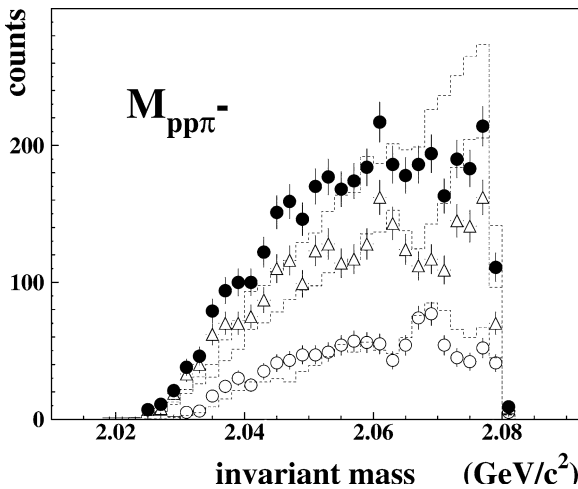


Fig. 2. Invariant mass spectrum  $M_{pp\pi^-}$  at  $T_p = 750$  MeV constrained with the condition  $M_{pp} < 1896$  MeV/ $c^2$ . The triangles show events, where the delayed pulse has been recorded in the same element where the  $\pi^+$  particle stopped. The open circles show events, where the delayed pulse has been recorded by a neighbouring element only. The solid dots give the sum of both event classes and represent the full experimental result. The dotted histograms show MC simulations assuming pure phase space, but including  $pp$  final state interaction (see Ref. [17]). Note that this spectrum is not yet corrected for detector efficiency and acceptance.

broad structure at 2.063 GeV/ $c^2$  in  $M_{pp\pi^-}$  with a statistical significance of about  $4\sigma$  relative to a MC simulation of the background process. Note, however, that if we account for statistical fluctuations of the background, too, then the significance of this structure reduces to  $2.6\sigma$  [20]. In this data analysis only those  $\pi^+$  events had been taken into account, for which a delayed pulse from the secondary  $\mu^+$  decay was observed in the *same* detector element in which the  $\pi^+$  particle was stopped. Because of the layer structure of the PROMICE/WASA forward range hodoscope this condition led to previously unknown inefficiencies of  $\pi^+$  detection for distinctive  $\pi^+$  ranges, and energies, respectively.

This situation is reexamined in Fig. 2, where we show the  $M_{pp\pi^-}$  spectra from the present work at 750 MeV with an order of magnitude more events than obtained in the test run. The spectrum is now decomposed into events with a delayed pulse recorded in the same detector element where the  $\pi^+$  stopped (triangles) and events with a delayed pulse recorded in a neighbouring element (open circles). Note that

positrons originating from  $\mu^+$  decay have a range in plastic detectors of up to 25 cm. Hence the chance of finding a delayed pulse in a neighbouring element and simultaneously none in the same element due to electronic thresholds is not negligible. We see that the correction due to delayed pulses in the neighbouring elements is largest in the mass range of 2065 to 2070 MeV/ $c^2$  corresponding to the transition region from the first to the second layer structure in the detector. The MC simulations now correctly reproduce these features. Adding up the events with delayed pulses in the same and in the neighbouring elements results in the solid dots, some structure at 2.063 GeV/ $c^2$  still remains visible, however, strongly diminished as compared to that in the data denoted by triangles. The artifact nature of at least part of the possible signal reported in Ref. [16] both in the  $M_{pp\pi^-}$  and the  $T_{\pi^+}$  spectra becomes obvious from this analysis.

We note that in another measurement [21] aiming to search for  $d'$  in this reaction also a bump near 2.06 GeV had been observed in  $M_{pp\pi^-}$ , if a constraint on low  $M_{pp}$  masses was imposed. These measurements conducted at  $T_p = 920$  MeV at ITEP had been carried out not on hydrogen but on C and CH<sub>2</sub> targets. Hence the events of interest had to be obtained by subtracting the C data from the CH<sub>2</sub> data. No follow-up studies have been undertaken to resolve the nature of that bump.

At the bottom of Fig. 1 the  $M_{pp\pi^+}$  spectra are presented for  $T_p = 750$  and 775 MeV. Again no structures of statistical significance are seen. Recall, however, the lower energy resolution in  $M_{pp\pi^+}$  which would wash out narrow structures. In Fig. 3 we finally show the differential cross sections for the  $M_{pp\pi^-}$  and  $M_{pp\pi^+}$  distributions following corrections for efficiency and luminosity, and acceptance extrapolated to  $4\pi$ . From the observed statistical fluctuations in these data we derive an upper limit (95% C.L.) for the production cross section of narrow (FWHM  $\lesssim 4$  MeV) dibaryons of  $\sigma_{\text{dibaryon}} \lesssim 20$  nb. With respect to  $d'$  this upper limit is already more than one order of magnitude below the theoretical prediction [18,22] of  $\sigma_{d'} \approx 300\text{--}1000$  nb.

The high-lying data point at 2087 MeV/ $c^2$  in the  $M_{pp\pi^-}$  spectrum taken at  $T_p = 775$  MeV deserves special consideration since its statistical significance is about  $3\sigma$  relative to the simulated spectrum and even

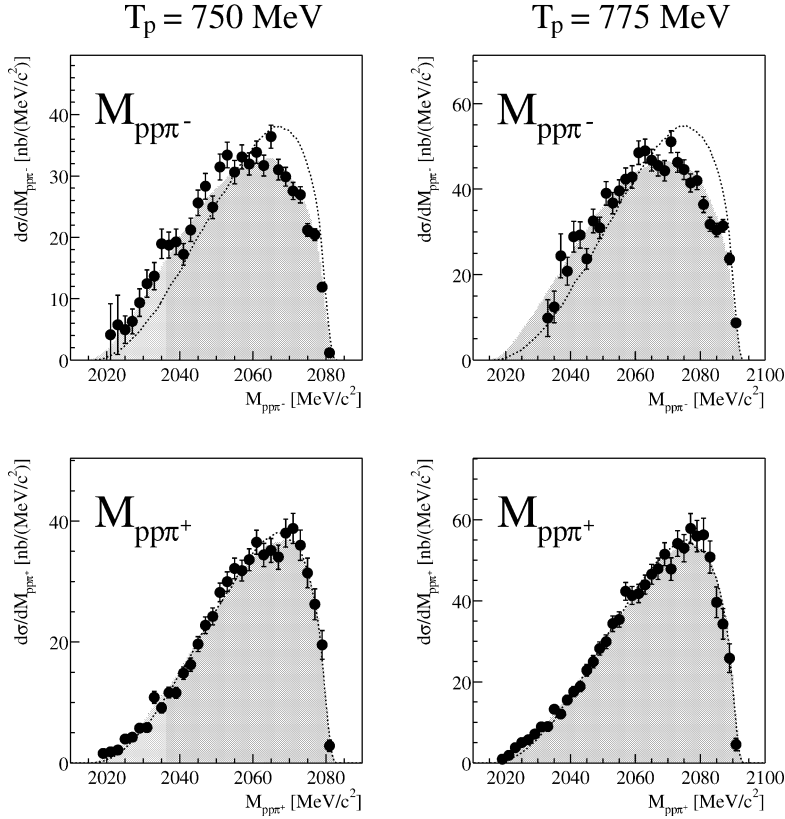


Fig. 3. Differential cross sections of the invariant mass distributions  $M_{pp\pi^-}$  (top) and  $M_{pp\pi^+}$  (bottom) at  $T_p = 750$  MeV (left [17]) and  $T_p = 775$  MeV (right). For the description of the curves see caption of Fig. 1.

higher relative to the neighbouring data bins. While this appears indicative of an existing structure we have to realize that there is a  $\approx 4\%$  probability for a  $3\sigma$  random excess in an arbitrary bin within a sample of 32 data bins such as in  $M_{pp\pi^-}$ .

The main reason however why we do not take this data point as evidence for a physical structure are possible systematic errors which are typical for data near the edges of the acceptance. The comparison of the 775 MeV raw spectra (Fig. 1) with the corresponding cross sections in Fig. 3 shows the fast fall-off of the acceptance as well as the effect of efficiency corrections towards higher energies. As a result in Fig. 3 the data point at 2087 MeV/c<sup>2</sup> is by far not as prominent as in Fig. 1. Moreover its exact value is very sensitive to details in the simulations such as the precise knowledge of particle thresholds and energy correction factors for particles close to threshold. Hence, the present experiment is inconclusive as to the origin of this excursion.

A clarification of its nature would require an experiment at higher incident energies such that this region moves into the fiducial range of the spectra.

#### 4. Conclusions

In conclusion, we have carried out exclusive measurements of the  $pp \rightarrow pp\pi^+\pi^-$  reaction, which is particularly well suited for the search for  $NN$  decoupled dibaryon resonances. We find no narrow structures neither in  $M_{pp\pi^+}$  nor in  $M_{pp\pi^-}$  within  $3\sigma$  of statistical significance, which could be indicative of dibaryon resonances in the mass range  $2022 < m < 2085$  MeV/c<sup>2</sup>. We derive an upper limit of 20 nb for their production cross section in this reaction. In particular for  $d'$  this finding implies a number of consequences: (i) either the  $d'$  does not exist at all; or (ii) its production cross section in  $pp$ -collisions is smaller

than expected from theoretical estimates [18,22]; or (iii) the mass of the free  $d'$  is outside the range investigated here; or (iv) it exists only in the nuclear medium. Medium effects on the  $d'$  are difficult to estimate theoretically. Ref. [23], e.g., predicts a decreasing dibaryon mass with increasing nuclear density. The DCX data which prompted the  $d'$  search, indeed exhibit a tendency of a decreasing peak energy, i.e., mass of the hypothetical  $d'$ , with increasing mass number of the nucleus [8].

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